10/ PRTS

10/506542
DT15 Rec'd PCT/PTO 03 SEP 2004.

WO 03/075054

PCT/EP02/02465

DEVICE FOR BENDING AN OPTICAL BEAM, IN PARTICULAR IN AN OPTICAL INTEGRATED CIRCUIT

The present invention relates to a device for bending, i.e. varying the direction of, a guided optical light, in particular for use in telecommunication optical integrated circuit.

In optical telecommunication systems, information is typically coded in short optical pulses by suitable optical sources, such as light-emitting diodes (LEDs) or semiconductor lasers, which pulses are transmitted along an optical-fibre network and received by photodetectors. Many different signals can be transmitted using a single wavelength of light by interweaving the pulses from different sources, a technique known as time-division multiplexing (TDM).

A simple way of increasing the amount of data that can be transmitted by a single optical fibre is to make the incoming electronic bits as short as possible. Current optical systems have achieved data rates up to 40 gigabits per second.

Recently, transmission capacity has been increased by dense wavelength division multiplexing (DWDM), which requires a very stable emitting laser and, at the receiver, very narrow linewidth filters and optical switches for separating individual wavelength channels and routing them to the appropriate destinations. Due to the large number of individual components in a DWDM system, integrated optical circuits have been developed. Integrated optical circuits may be either monolithic or hybrid and comprise active and passive components, typically realized on a semiconductor or dielectric substrate, used for coupling between optoelectronic devices and providing signal processing functions.

As described by *R. L. Espinola et al. in "A study of high-index-contrast 90° waveguide bend structures", OPTICS EXPRESS, Vol. 8, No. 9, pp. 517-528, 23 April 2001*, low-cost, highly-functional optical integrated circuits require a material system with relatively high refractive index contrast in order to increase the packing density of the optical elements, and also the use of sharp, e.g. 90°, bends. However, low-loss sharp bends cannot be easily achieved with standard waveguide technology because waveguide loss increases exponentially with the inverse bend radius.

New approaches to achieving sharp bends have therefore been considered. For example, it has been proposed to use waveguide corner mirrors, which

exploit strong modal confinement and total internal reflection (TIR) at the corner, as described by *W. Yang and A. Gopinath in "Design of planar optical waveguide corners with turning mirrors", Proceedings of Integrated Optics, Technical Digest Series, Vol. 6 (optical Society of America, Washington, D.C., 1996), pp. 58-63*. With suitable mirror placement and angle, these structures can reflect the incident light with low-loss in the bend.

Another widely-studied approach to low-loss bends is that using high-index-contrast waveguides, whose strong light confinement properties allow performing complex waveguide interconnections within a small area. *C. Manolatou et al, in "High-Density Integrated Optics", Journal of Lightwave Technology, Vol. 17, No. 9, September 1999*, pp. 1682-1692, show that by modifying the waveguide intersection regions into resonant structures with simmetry, right angle ends, T-junctions, and crossing with high transmission characteristics are also possible using conventional single-mode high index-contrast waveguides.

The Applicant observes that the very small dimensions of high-index-contrast waveguides cause difficulties in coupling light at their input and relatively high scattering losses.

Recently, the use of photonic crystal waveguides has been proposed for making high transmission 90°-bends, as described by *A. Mekis et al. in "High transmission through sharp bends in photonic crystal waveguides", Phys. Rev. Lett. 77, 3787-3790 (1996)*. In this case, photonic band-gap (PBG) materials are modified by inserting a line of defects that can support a localized mode having a frequency located within the photonic bandgap, as described by *R. D. Meade et al. in "novel application of photonic band gap material: Low-loss bends and high Q cavities", J. Appl. Phys. 75, 4753-4755 (1994)*. The defect line thus supports a local state and acts as a waveguide. An efficiency near to 100% has been observed at certain frequencies near the valence band edge for λ~1.55 μm for a 60° photonic-crystal waveguide bend in *E. Chow et al., "Quantitative analysis of bending efficiency in photonic-crystal waveguide bends at λ=1.55 μm wavelengths", Optics Letters, Vol. 26, No. 5, March 1, 2001, pp. 286-288.*

US 5,526,449 discloses an optical circuit and a method for substantially eliminating radiation losses associated with optical integrated circuits and, in particular, bends in optical waveguides. The circuit and waveguide are fabricated on

a substrate having a periodic dielectric structure. The periodic dielectric structure exhibits a range of frequencies of electromagnetic radiation that cannot propagate into the structure, i.e. a photonic band gap. Radiation at a frequency within the frequency band gap of the structure is confined within the circuit and waveguide by the periodic dielectric structure surrounding the circuit and waveguide.

US 6,134,369 describes a compact optical waveguide employing a photonic band gap element as a reflector to enable a light beam to be reflected at angles greater than the critical angle. The photonic band gap element is a two-dimensional array of columnar holes formed in the substrate, the holes being filled with air or another material having a different dielectric constant than the substrate. The optical waveguide forms a right angle bend and first and second photonic band gap elements are formed on the inside and outside of the bend to deflect light which is incident on the waveguide at an angle greater than a critical angle defined by the materials that constitute the optical waveguide.

Besides development of photonic crystals devices having defects, behaviour of light in photonic crystals having regular periodicity, herein below referred to as “regular photonic crystals” for simplicity, has been investigated. For the purposes of the present invention, with "photonic crystals having regular periodicity" it is intended a photonic crystal wherein the characteristics of its periodic array do not vary at least in a region thereof of intended light propagation.

The article of *P. Etchegoin and R. T. Phillips, “Photon focusing, internal diffraction, and surface states in periodic dielectric structures”, Physical Review B, Volume 53, Number 19, 15 May 1996-1*, takes advantage of some analogies between electrons in semiconductors and electromagnetic waves in periodic dielectric structures for providing a method for calculation the band structure of a 2-D periodic dielectric structure. Moreover, this article deals with the phenomenon of photon focusing emitted by a source point in these structure, in analogy with the phenomenon of acoustic phonon focusing, showing what shape shall have the k_x-k_y diagram of the wave vector $\underline{k}$ to have focusing of light along predetermined directions.

The Applicant observes that the phenomenon of photon focusing, which has been studied only at theoretical level, would find only limited applications in integrated optics.

The article of *Marko Lončar, Jelena Vučkovič and Axel Scherer, “Three-*

dimensional analysis of dispersion properties of planar photonic crystals", Proceedings of PECS III conference (June 2001), St. Andrew's, Scotland. shows that a planar (i.e. 2-D) photonic crystal may have, under certain conditions, a self-collimation effect in the second energy band (i.e. the energy band over the fundamental band). As disclosed in the article, these conditions determine a negative group velocity.

The Applicant observes that, for the time being, no practical applications have been shown of a beam of light (although collimated) having a negative group velocity.

The Applicant has found that high-efficiency sharp bending in an integrated optical circuit can be obtained by using an opportunely designed photonic crystal associated to a reflecting surface. In fact, the Applicant has found that a photonic crystal can be made suitable to guide a beam of light in a collimated way in a portion thereof of regular periodicity, if an opportune relation exists between predetermined crystal properties and the considered wavelength, and has moreover found that such a crystal can be provided with a reflecting surface so as to realize a device for sharp bending with negligible losses an optical beam between two waveguides.

Therefore, the present invention relates to a device for varying the direction of an optical beam, comprisinga first waveguide directed along a first direction, a second waveguide directed along a second direction different from the first direction, and a bending region interposed between the first and the second waveguide, wherein the bending region comprises a photonic crystal having a regular periodicity and having at least a first and a second crystal axes substantially aligned with said first and second directions, and a reflecting surface delimiting said photonic crystal and so positioned and oriented as to reflect an optical beam coming from the first waveguide towards the second waveguide.

The photonic crystal preferably comprises a slab of dielectric material and the reflecting surface is preferably realized by removing a portion of said slab.

The first and second directions may be perpendicular to each other. This situation occurs, for example, when the photonic crystal has a periodic array of holes arranged according to a square geometry.

Alternatively, the first and second directions may define and angle of $\pi/3$, for example when the photonic crystal has a periodic array of holes arranged according

to a triangular geometry.

At least one of the first and second waveguide may be an optical integrated waveguide, or alternatively an optical fibre.

Preferably, the photonic crystal is made of a bulk material with a first refractive index and has a periodic array of regions with a second refractive index different from the first and with predetermined radial dimensions; the optical beam having a wavelength so related to the difference between said first and second refractive indices, to the radial dimensions of said regions and to the period of said array that, starting from a isotropic distribution of the wave vectors of said electromagnetic radiation within a first angular range that is twice the angular extension of the first irreducible Brillouin zone of said photonic crystal, the group velocity vectors corresponding to said wave vectors are so rearranged during propagation in said photonic crystal that at least 50% of the group velocity vectors become directed within a second angular range that is about one-third of said first angular range and the width at half-maximum of the distribution of the modules of said group velocity vectors is lower than about two-third of said second angular range.

Further details may be obtained from the following description, which refers to the accompanying drawings listed below:

Figure 1 is an illustrative representation of a 2-D photonic crystal having a regular periodicity;

Figure 2a schematically shows a device for propagating a light beam through a photonic crystal according to the present invention, and **2b** show a possible arrangement (triangular in this case) of the holes in a photonic crystal;

Figure 3 is an illustrative representation of an energy band diagram for a photonic crystal having a triangular array of holes;

Figure 4a and **4b** show diagrams of wave-vectors $\underline{k}$ and group velocities $\underline{v}_g$ suitable for observing waveguiding in a photonic crystal;

Figure 5 is an illustrative representation of the distribution of group velocities $\underline{v}_g$ in the direction of a crystal axis;

Figure 6 is an illustrative perspective view of a device for waveguiding electromagnetic radiation according to the present invention;

Figure 7a and **7b** show possible X-crossing devices made in accordance to

the present invention;

Fig. 8 shows a device for producing a sharp bend of a light beam, according to the present invention; and

Figures 9a-9d, 10a-10d, 11, 12 and **13** relate to results of numeric simulations.

With reference to **Figs. 1, 2a** and **2b,** it is indicated with 1 a photonic crystal comprising a bulk body 2 made of a dielectric material, wherein a periodic array of holes 2 has been realized. Although a bi-dimensional (2-D) photonic crystal is described, the teaching of the present invention may be extended to three-dimensional (3-D) photonic crystals as well, i.e. crystals having a 3-D distribution of regions of different refractive index than the bulk, such as spheres.

The bulk dielectric material has a refractive index *n* preferably greater than 1.5. Possible materiales are SiO_2, SiO_xN_y, GaAs, Si; this list is only illustrative and not exhaustive.

Preferably, holes 2 contain air, are cylindrical and parallel to each other and have a same radius ρ. As shown in **Fig. 2b**, holes 2 may be arranged to form a triangular array having a period *a*. Although an arrangement according to an equilateral triangle is illustrated, an arrangement according to an isosceles triangle may be used, as well. Alternatively, holes 2 may be arranged according to a square or a rectangular array. In general, the periodicity of the array is the periodicity of the "cells", each "cell" including three holes for triangular arrays and four holes in square or rectangular arrays.

It can be shown that the preferred transmission directions are those corresponding with the crystal axes. In case of triangular geometry, the crystal axes are those connecting the vertices of the triangles, while in case of square or rectangular geometries the crystal axes correspond to the diagonals of the square or triangle, i.e. the axes connecting opposite vertex. In case of triangular array geometry the three crystal axes are angularly spaced at 60° ($\pi/3$), while in case of square array geometry the two crystal axes are angularly spaced at 90° ($\pi/2$).

Although the description that follows is referred to a photonic crystal having holes 2 filled with air and of circular cross-section, the teaching of the present inventions extends to photonic crystals wherein the holes contain a predetermined substance different from air or are substituted by rods of a predetermined dielectric

material (of different refractive index than the bulk dielectric material), and wherein the holes have cross-sections other than circular, for example square.

In accordance with the above, photonic crystal 1 has a structure that does not vary along an axis z parallel to the axes of holes 2, and that varies periodically in a plane x-y perpendicular to axis z.

Method of manufacturing photonic crystal 1 will not be described in that methods known in the art can be used. Methods for manufacturing photonic crystals and devices comprising photonic crystals are described, for example, in US 5,526,449, US 6,064,511 and in the article of *M. Lončar, T. Doll, J. Vučkovič and A. Scherer, "Design and Fabrication of Silicon Photonic Crystal Optical Waveguides", Journal of Lightwave Technology, Vol. 18, No. 10, October 2000.*

The parameters that determine the guiding characteristics of the photonic crystal 1 are the relative spacing R, defined as the ratio between the period a of the array of holes 2 and the radius ρ of holes 2, the refractive index n of the dielectric material (or, in general, the difference of refractive index between the bulk dielectric material and the substance or material filling the holes), and a further parameter, known as "normalized frequency" and indicated with ω_n, proportional to the ratio between the period a and the wavelength λ of the electromagnetic radiation to be guided.

The condition of "photon guiding", or "waveguiding", is achieved if the photonic crystal 1 is so designed, and the electromagnetic radiation propagating therein has such a wavelength, that a substantial fraction of the energy of the electromagnetic radiation is made to flow in a direction coinciding with one of the crystal axes. The "photon guiding" condition will herein below defined by reference to a well-known vector parameter of the electromagnetic radiation, the "group velocity", whose direction corresponds to that of energy propagation. In practice, starting from an isotropic distribution of group velocities, "photon guiding" occurs when said distribution is so modified that:

- a predetermined percentage of the group velocities is oriented within a predetermined sub-range of the original angular range;
- the angular distribution of the module of the group velocities shows a peak along the considered propagation axis, and has a width at half-maximum lower than a predetermined value.

In other words, the photon crystal shall be so designed that the group velocies converge towards the desired propagation direction and that most of the energy of the propagating beam is carried by the group velocities so directed.

For the purposes of the present invention, a condition of "photon guiding" of an electromagnetic radiation in a predetermined direction within a photonic crystal is a condition wherein, starting from a isotropic distribution of the wave vectors of said electromagnetic radiation within a first angular range that is twice the angular extension of the first (irreducible) Brillouin zone of the photonic crystal, the group velocity vectors corresponding to said wave vectors are rearranged as concerns direction and module so that at least 50% of the group velocity vectors become directed within a second angular range that is about one-third of the first angular range and the width at half-maximum of the distribution of the modules of said group velocity vectors is lower than about two-thirds of the second angular range.

In a preferred condition, the width at half-maximum of the distribution of the modules of said vectors is lower than about one-half of the second angular range.

In the description that follows, the angular distribution of the group velocity will be indicated with as r(θ).

In the previous definition of "photon guiding", as in the following of the present description, the width at half-maximum of a distribution r(θ) will be considered as equivalent to the variance of the distribution, wherein the variance σ is so defined:

$$\sigma = \sqrt{\frac{\sum_i (\theta_i - \mu)^2 \cdot r(\theta_i)}{\sum_i r(\theta_i)}}$$

where θ_i indicates the angle with respect to the considered direction, and μ is the average of said distribution about said direction and is equal to 0 for a triangular array and to $\pi/4$ for a square array .

Preferred conditions for photon guiding may be expressed in terms of variance σ. In case of a triangular geometry, a preferred condition of "photon guiding" along a crystal axis occurs when, starting from a isotropic distribution of the wave vectors within an angular range of 60° ($\pi/3$) about said axis (which is twice the

angular extension of the first irreducible Brillouin zone), the group velocity vectors corresponding to said wave vectors are rearranged, as concerns module and direction, so that at least 50% of the group velocity vectors become directed within an angular range of 20° ($\pi/9$) about said axis (i.e. within an angular range that is one-third of the original one) and the variance σ of the module distribution about said axis is lower than about 0.15 rad (i.e. $\sigma^2 <\sim 0.022$ rad^2). A better guiding effect may be observed for σ lower than about 0.13 rad (i.e. $\sigma^2 <\sim 0.017$ rad^2) and a still better guiding effect for σ lower than about 0.11 rad (i.e. $\sigma^2 <\sim 0.012$ rad^2). Choosing a more or a less restrictive condition (in terms of σ) may depend on the particular requirements and conditions, for example on the distance to be covered through the photonic crystal.

In case of a square geometry, a preferred condition of "photon guiding" along a crystal axis occurs when, starting from a isotropic distribution of the wave vectors within an angular range of 90° ($\pi/2$) about said axis (which is twice the angular extension of the first irreducible Brillouin zone), the group velocity vectors corresponding to said wave vectors are rearranged, as concern module and direction, so that at least 50% of the group velocity become directed within an angular range of 30° ($\pi/6$) about said axis (i.e. within an angular range that is one-third of the original one) and the variance σ of the module distribution about said axis is lower than about 0.22 rad (i.e. $\sigma^2 <\sim 0.049$ rad^2). A better guiding effect may be observed for σ lower than about 0.17 rad (i.e. $\sigma^2 <\sim 0.029$ rad^2) and a still better guiding effect for σ lower than about 0.12 rad (i.e. $\sigma^2 <\sim 0.014$ rad^2).

Propagation under "photon guiding" further requires that the electromagnetic radiation has a wavelength in the fundamental photonic band. It can be shown that the above condition of "photonic guiding" is achieved where the surface of the fundamental energy band (in the ω, k_x, k_y space) shows an inflection.

Therefore, differently from waveguiding into conventional photonic crystals, wherein light at a wavelength within the photonic band-gap is conveyed through a localized and unchangeable waveguide typically defined by a line of defects in the photonic crystal, waveguiding into a photonic crystal according to the present invention can occur at a wavelength within the photonic fundamental band and in any region of the photonic crystal of regular periodicity. In practice, a "virtual waveguide" is created when a beam of light is made to propagate into a photonic crystal

according to the present invention, since the particular propagation conditions "observed" by the beam of light force it to collimate.

It can therefore be appreciated that the photonic crystal of the present invention does not require any physical waveguide structure such as the linear defect regions of conventional photonic crystals. Dimension and position of a collimated guided beam in the photonic crystal of the present invention are determined by, and correspond to, dimension and position of the input light beam, while the possible propagation directions are those correspond to the crystal axes.

Therefore, if photonic crystal 1 is optically coupled to an optical source suitable to emit electromagnetic radiation at a predetermined wavelength, and if this wavelength is so related to the physical characteristics of the photonic crystal 1 to satisfy the conditions for photon guiding, a device suitable to guide a beam of light at this wavelength can be realized. **Fig. 2a** shows schematically an optical source 4, for example a known type of laser, optically coupled to photonic crystal 1 by means of a first optical waveguide 5 of a known type, for example an optical fibre or an integrated optical waveguide. A second optical waveguide 7 of a known type is coupled to the photonic crystal 1 opposite the first waveguide 5. Also schematically represented is a beam of light 6 generated by the optical source 4 and fed to the photonic crystal 1 via the first waveguide 5, which is then propagated substantially collimated into the photonic crystal 1 and exits the photonic crystal 1 via the second waveguide 7.

A further important characteristic of the photonic crystal of the present invention is that a plurality of light beams, possibly of different dimensions and directions, can be transmitted simultaneously in the crystal. In particular, it is possible to transmit two or more light beam in the crystal that cross each other so as to define a "X-crossing" structure. The Applicant has verified that in such a crossing there is no interaction (i.e., no cross-talk) between the electromagnetic fields of the two beams. Possible X-crossing will be described in the following.

A same photonic crystal according to the present inventions may be therefore applied in different ways, for example for guiding a plurality of parallel light beams evenly or differently spaced from each other and having the same or different dimensions, or for guiding a plurality of light beam propagating along different directions (coinciding with crystal axes) and having the same or different directions, which may cross each other in a same or in different regions of the crystal (for

example: a beam propagating in a first direction may cross, one after the other, two further beams propagating in a second direction; three beams propagating in three different directions may cross in a same region).

When a plurality of optical beams are propagated, these beams may have a same wavelength or different wavelengths, provided that these wavelengths are suitable for photon guiding in the considered photonic crystal according to the teaching of the present invention.

The Applicant has verified that preferred ranges of the relevant parameters n, R and ω_n for achieving the said condition of "photon guiding" are, for triangular and square array geometries, the following:

- for triangular array geometry:
  - relative spacing R: between 0.15 and 0.5, more preferably between about 0.20 and 0.45, still more preferably between about 0.25 and 0.4;
  - refractive index n: between 1.5 and 4.5, more preferably between 2.5 and 3.5;
  - normalized frequency ω_n: between about 0.17 and 0.42, more preferably between about 0.25 and 0.40.
- for square array geometry:
  - relative spacing R: between 0.15 and 0.5, more preferably between about 0.20 and 0.45, still more preferably between about 0.25 and 0.4;
  - refractive index n: between 1.5 and 4.5, more preferably between 2.5 and 3.5;
  - normalized frequency ω_n: between about 0.17 and 0.42, more preferably between about 0.25 and 0.40

As described in the following, there is a relation among these three parameters, so that when two of the three parameters are chosen, the third is fixed.

To find the optimum value ranges of the relevant parameters R, n and ω_n, the following method can be followed.

The method comprises analysing the group velocity distribution resulting from the possible combinations of values of the parameters R, n and ω_n within predetermined ranges and determining the set of combinations that provide a group

velocity distribution suitable to have photon guiding according to the above teaching.

To this aim, a theoretical model the crystal, such as the model proposed in the above-cited article of *P. Etchegoin and R. T. Phillips*, may be advantageously applied. This model can be initially used for determining the band diagram of the crystal when a couple of values of n and R has been established and can be then used to determine the distribution of the group velocities when predetermined values of R, n and ω_n are considered.

If a 2-D dielectric structure as in **Fig. 1** is considered, in particular having an extension along the x and y axes much greater than along the z-axis, an electromagnetic band structure as in the illustrative representation of **Fig. 3** is obtained, where Γ, M and K are the well-known parameters identifying the first Irreducible Brillouin zone, and the continuous and dashed lines correspond to the TE and TM modes, respectively. As concerns the TE modes, a fundamental photonic band (or first band), here indicated with BAND I, and a photonic band-gap PBG, separating the fundamental band BAND I from a second photonic band BAND II, may be identified.

As known from theory of electromagnetic propagation in anisotropic media, energy does not flow in the same direction of $\underline{k}$. When energy is represented by dispersion relation $\omega(\underline{k})$, it is easily demonstrated that energy flows in the direction of the group velocity $\underline{v_g}=\underline{\nabla_k}\cdot\omega(\underline{k})$. In fact, it can be shown formally that $\underline{v_g}$, obtained as a gradient of $\omega(\underline{k})$, coincides with the direction of the Poynting vector $\underline{S}\propto\underline{E}x\underline{H}$ for electromagnetic waves. Therefore, the electromagnetic band structure provides a relation $\omega=\omega(\underline{k})$, from which the group velocity $\underline{v_g}$ can be obtained.

For a predetermined energy it is possible to define two surfaces: the constant energy surface, represented in the k_x-k_y plane, obtained directly by the intersection of the 3-D band surface (in the space ω, k_x, k_y) with a plane with constant abscissa equal to given energy value; and the wave surface, formed by the locus of all possible group velocities and represented in the v_{gx}-v_{gy} plane. The wave surface represents the wave front that would emerge from a point source. It can be shown that, for each point of the constant energy surface, the corresponding group velocity is directed perpendicular to said surface. Said article *P. Etchegoin and R. T. Phillips* illustrates possible shapes for these surfaces for photon focusing.

In order to have a collimated guiding of light within the crystal, these

surfaces shall have particular shapes, in particular the constant energy surface (in the k_x-k_y plane) shall have straight portions with the broadest possible extension, and the group velocities shall be directed outwards with respect to the centre of the diagram. The wider and the flatter are said portions, the larger will be the range of group velocities having the same direction (i.e. the more collimated will be the guided light). In a triangular array geometry, to have a substantially collimated transmission, the constant energy surface shall have a substantially hexagonal shape, with straight portions defining the edges of the hexagon. Differently, in a square array geometry, the constant energy surface shall have a substantially square shape, and the group velocities will be highly concentrated in the directions perpendicular to the four edges, i.e. in four different directions equally angularly spaced (of $\pi/2$).

Fig. 4a shows, illustratively, a constant energy surface (k_x-k_y plane) of a type suitable for having collimated guiding in case of a triangular array geometry and for the TE mode of a monomode electromagnetic radiation, and **Fig. 4b** shows the corresponding wave surface (v_{gx}-v_{gy} plane).

In the simulation, a isotropic distribution of group velocities about a predetermined crystal axis in an angular range of $\pi/3$ for a triangular array, and of $\pi/2$ for a square array, has to be considered as a starting condition, and the parameters R, n and ω_n may be varied for example as follows.

The parameter R may be varied in a range that is chosen by taking into account the current technological difficulties in realizing large aspect ratio holes arrays in photonic crystals. A suitable range is for example between 0.15 and 0.45.

The parameter n may be is varied in a range of values including those of the currently most suitable dielectric materials for the manufacturing of photonic crystals, such as SiO_2, SiO_xN_y and GaAs: for example the values 1.5, 2, 2.5, 3.25 and 3.5 may be considered.

The third parameter ω_n may be varied of a predetermined amount (for example $1 \cdot 10^{-4}$) in a predetermined range, for example starting from the maximum value $\omega_{n,max}$ of the first band, until a predetermined condition is satisfied, as explained below.

The simulation model previously mentioned may be advantageously applied in this stage to each couple of values of R and n within the specified ranges, determining each time the value of ω_n that optimizes the distribution of the group

velocity $r(\theta)$.

In particular, for each couple of values of R and n, the parameter ω_n is varied of the predetermined amount until the group velocity distribution $r(\theta)$ is optimised in terms of average μ, variance σ, height Δh, kurtosis K and percentage of representative points that are within a predetermined angular range $\Delta\theta$ about the considered direction. This angular range, as previously stated, is chosen equal to $\pi/9$ for a triangular array geometry and $\pi/6$ for a square array geometry. In particular, the optimum value of ω_n is the one that minimizes σ and K and maximizes Δh and the percentage of points within the angular range $\Delta\theta$. **Fig. 5** is an illustrative representation of a group velocity distribution, with an indication of the said parameters, which are defined as follows (definition of σ is reported again for sake of clarity):

$$\Delta h = \frac{\max\left(r(\theta)\big|_{|\theta|<\Delta\theta} \right) - \min\left(r(\theta)\big|_{|\theta|<\Delta\theta} \right)}{\min\left(r(\theta)\big|_{|\theta|<\Delta\theta} \right)};$$

$$\sigma = \sqrt{\frac{\sum_i (\theta_i - \mu)^2 \cdot r(\theta_i)}{\sum_i r(\theta_i)}}$$

where $\mu=0$ for a triangular array and $\mu=\pi/4$ for a square array ; and

$$K = \frac{\sum_i (\theta_i - \mu)^4 \cdot r(\theta_i)}{\sum_i r(\theta_i)}.$$

When ω_n is equal to its optimum value, the curve of the group velocity distribution is relatively sharp and has the maximum height Δh. If ω_n is varied in one direction or the other with respect to its optimum value, the distribution undergoes an abrupt decrease of Δh, and an increase of the kurtosis K and of the variance σ. In particular, variations of the parameter ω_n with respect to said optimum condition determine either a broadening of the distribution or the appearance of a ring in the curve, and it can be demonstrated that both conditions are undesirable.

When the optimum value of ω_n is found for a predetermined couple of values

of n and R, it is checked if the values of the variance σ and of the percentage of points within the specifies angular range for the considered tern of values of n, R and ω_n satisfies the above-mentioned conditions for photon guiding.

All the terns of value of R, n and ω_n so detected identify a crystal structure, a bulk material and a wavelength suitable to have photon guiding.

Fig. 6 illustrates an integrated optical device 200 comprising a substrate 207 and a plurality of layers superimposed on a z direction, in particular a decoupling layer 202, a first cladding layer 203, a core layer 204 and a second cladding layer 205. The refraction index of the core layer 204 is higher than that of the first and second cladding layers 203, 205. The refractive index of the decoupling layer 202 is lower than that of the first cladding layer 203.

Moreover, device 200 has a periodic array of holes 2 that cross layers 205, 204, 203 and 202 along the z direction down to the substrate 207, thus defining a photonic crystal 201. Photonic crystal 201 is designed according to the present invention. Besides providing a photon guiding effect in a x-y plane, device 200 also confines light in the z direction inside the core layer 204, due to the difference of refraction index of the core layer 204 with respect to the first and second cladding layers 203, 205.

Photonic crystal 201 may be interfaced with different types of conventional waveguides for the input and the output of light, such as ridge waveguides (with shallow edge or deep edge, the latter being also known as “mesa”), rib waveguides, photonic crystal waveguides (with linear defect regions). The input and output of light may be also performed by means optical fibers, in particular by facing the core of the fiber to the core layer 204. In the illustrative example of **Fig. 6**, device 200 includes a mesa waveguide 210 integrally connected to the photonic crystal 201. Mesa waveguide 210 extends along a direction corresponding to one of the crystal axes of the photonic crystal 201 and has a succession of layers corresponding to those of photonic crystal 201 so that, in the manufacturing process, it may be grown together with photonic crystal 201.

As an example, a device suitable to operate at 1550 nm has a substrate 207 made of GaAs having a refractive index (measured at 25°) of 3.374, a core layer 204 made of $Al_{0.37}Ga_{0.63}As$ having a refractive index (measured at 25°) of 3.25, first and second cladding layers 203, 205 having a refractive index of 0.01 lower than that of

the core layer 204 (by using a different percentage of Al), and a decoupling layer 202 that, in turn, has a refractive index of 0.01 lower than that of the cladding layers 203, 205 (by using a different percentage of Al). The characteristic parameters of the considered photonic crystal are n=3.25, R=0.42 and ω_n=0.26. The radius ρ of holes 2 is 93 nm and the period a of the array is 311 nm. Holes 2 are arranged according to a triangular array and are filled of air.

Such a device provides a k_x-k_y and v_{gx}-v_{gy} diagrams as those represented in **Figs. 4a** and **4b**.

Device 200 is only an illustrative example and, in general, a photonic crystal according to the present invention may be used in any type of planar waveguiding structure able to confine light in the z direction.

Fig. 7a and **7b** are illustrative representation of two different X-crossing devices 300, 400 that make use of a photonic crystal according to the present invention, with a triangular and square arrangement of holes 2, respectively. In particular, device 300 comprises a hexagonal photonic crystal structure 301 having a periodic array of holes 2 with equilateral triangular array geometry, and three couples of opposite waveguides 302, 303, 304 directed along the crystal axes, here indicated with x_1, x_2 and x_3. Each couple of waveguides 302, 303, 304 includes an input waveguide 302', 303', 304' and an output waveguide 302", 303", 304". Waveguides 302, 303 and 304 may be, for example, conventional waveguides in integrated optics, or be defined by linear defects regions of a photonic crystal. Alternatively, in place of one or more of waveguides 302, 303 and 304, there may be a corresponding optical fiber (not shown) facing the edge of the photonic crystal.

In use, three different beams of light A, B, C, carrying respective signals and having a same wavelength or close different wavelengths suitable for photon guiding, are fed to the photonic crystal 301 via the input waveguides 302', 303', 304' and propagate collimated into the photonic crystal 301. In the centre of the photonic crystal 301, the three beams A, B, C cross each other. It has been verified that this crossing occurs without mutual interaction among the beams, i.e. without cross-talk. After crossing, the beams continue their propagation to reach the respective output waveguides 302", 303", 304" so that they can exit the device.

A device with an isosceles triangle array geometry may alternatively be used, and the directions of the input and output waveguides shall be varied

accordingly, in order to coincide with the directions of the crystal axes.

It can be appreciated that a couple of waveguide may be omitted from device 300, so as to have a device that is simpler but is suitable for crossing only two beams of light.

Device 400 comprises a square photonic crystal structure 401 having a periodic array of holes 2 arranged according to a square geometry, and two couples of opposite waveguides 402, 403 directed along the crystal axes, here indicated with x and y. Each couple of waveguides 402, 403 includes an input waveguide 402', 403' and an output waveguide 402", 403". Waveguides 402, 403 may be, for example, conventional waveguides in integrated optics, or be defined by linear defects regions of a photonic crystal. Alternatively, in place of one or both of waveguides 402, 403, there may be a corresponding optical fiber (not shown) facing the edge of the photonic crystal.

In use, two different signals A and B are fed to the photonic crystal 401 via the input waveguides 402', 403', propagate collimated into the photonic crystal 401, cross each other in the centre thereof without mutual interaction, and continue their propagation by entering the output waveguides 302", 303", 304". Therefore, two different beams of light can cross each other without crosstalk along two directions at 90° to each other.

A device comprising a rectangular structure and/or a rectangular geometry of the array of holes 2 may be used as well.

Fig 8 shows a device 500 for sharply bending a beam of light. Device 500 comprises a slab 501 of dielectric material of refractive index n_1 that defines, in a portion thereof, a photonic crystal 502 according to the present invention. In the particular example here illustrated, the photonic crystal 502 has a periodic array of holes 2 with square geometry and has therefore two perpendicular crystal axes x, y. One portion of slab 501 has been removed by known techniques so as to define an air gap 505, i.e. a region of space with refractive index n=1. The interface between the photonic crystal 502 and the air gap 505 defines a reflecting surface 506. Surface 506 is so oriented that the normal to surface 506 bisects the two crystal axes x, y. The region occupied by the photonic crystal 502 and delimited by reflecting surface 506 defines a bending region of the device.

Device 500 further comprises a first (or input) and a second (or output) waveguide 507, 508 of a known type, made of a material having a second refractive

index n_2 different from n_1. First and second waveguides 507, 508 are directed along the crystal axes x and y, respectively, and end at the borders of the photonic crystal 502.

In use, one of the two waveguides, for example the first waveguide 507, conveys a beam of light A into the photonic crystal 502. The photonic crystal 502, if the wavelength of the beam A is so related to the refractive index n_1 and to the period and radius of the holes 2 as previously described (i.e. so as to satisfy the "photon guiding" condition), guides the beam A along axis y to the reflecting surface 506 and, after reflection, along axis x to the second waveguide 508, where it is newly conveyed in a conventional way.

It can be appreciated that the reflecting surface may be defined in different ways, for example by providing an interface different from air.

The array of holes may also have a different geometry, such as rectangular or triangular. In case of triangular array geometry, reflection may occur at different angles, provided the normal to the reflecting surface bisects the two considered propagation axes; for example, when holes are arranged according to an equilateral triangle, reflection may occur at 60° ($\pi/3$) or 120° ($2\pi/3$). Input and output waveguides shall be oriented accordingly.

Waveguides for the input and the output of light may be any type of known integrated optical waveguides, such as ridge waveguides (with shallow edge or deep edge, the latter being also known as "mesa"), rib waveguides, or photonic crystal waveguides (with linear defect regions).

As an alternative, one or both of the input and output waveguide may be an optical fibre facing laterally the slab comprising the photonic crystal.

Example 1

In a first set of simulations, it is shown how the characteristics parameters R, n and ω_n can be selected for achieving photon guiding. The simulation model previously described has been used for determining the group velocity distributions for different combination of values of said parameters. A photonic crystal having a (equilateral) triangular array of air holes and an initial isotropic distribution of the group velocities has been considered. The analysis is limited to the first dispersion

band of the mode TE and it is performed by expressing the group velocity in polar coordinates.

A isotropic distribution of group velocities about a predetermined crystal axis in an angular range of $\pi/3$ for a triangular array, and of $\pi/2$ for a square array, has been considered.

The parameter R has been varied between 0.15 and 0.45 by steps of 0.3; as concern the parameter n , the values 1.5, 2, 2.5, 3.25 and 3.5 have been considered; the parameter ω_n has been varied of steps of $1 \cdot 10^{-4}$.

Figs. 9a-9d show the group velocity distributions for R=0.21 and n varying in the set of values 2, 2.5, 3.25 and 3.5. The abscissa axis represents the angles (in rad) and the ordinate axis indicates the normalized value of the group velocity. For each graph, the optimum value of ω_n has been found by varying this parameter by steps of $1 \cdot 10^{-4}$. Electromagnetic radiation of polarization TE and wavelength in the fundamental photonic band has been considered.

Table I reports, for the different curves of **Figs. 9a-9d**, the value of n and the optimum value of ω_n , together with the values of the square of variance (σ^2), of the kurtosis (K), of the height of the group velocity angular distribution (Δh), and of the percentage of points (N) originally in a range of $\pi/3$ about the considered propagation direction that have been concentrated within an angular range of $\pi/9$.

TABLE I (R=0.21)

	n	ω_n	σ^2[rad^2]	K [rad^4]	Δh	N [%]
Fig. 9a	2	0.2954	$2.5101 \cdot 10^{-2}$	$3.41 \cdot 10^{-3}$	0.35	38
Fig. 9b	2.5	0.2377	$2.0244 \cdot 10^{-2}$	$4.08 \cdot 10^{-3}$	1.77	53
Fig. 9c	3.25	0.1839	$1.7702 \cdot 10^{-2}$	$4.46 \cdot 10^{-3}$	2.5	62
Fig. 9d	3.5	0.171	$1.7793 \cdot 10^{-2}$	$4.8 \cdot 10^{-3}$	2.56	64

It can be observed that the distribution of **Fig. 9a** is unsuitable for photon guiding (according to the above-mentioned conditions), while the distributions of **Figs. 9b-9d** have values of σ and N suitable for photon guiding.

Figs. 10a-10d show the group velocity distributions for R=0.27 and n varying as above (2, 2.5, 3.25 and 3.5). As previously, the value of ω_n providing the best

distribution has been chosen in each graph.

Table II reports, for the different curves of **Figs. 10a-10d**, the values of the characteristics parameters.

TABLE II (R=0.27)

	n	ω_n	σ^2[rad^2]	K [rad^4]	Δh	N[%]
Fig. 10a	2	0.3059	$1.6973 \cdot 10^{-2}$	$4.46 \cdot 10^{-3}$	3.18	64
Fig. 10b	2.5	0.2479	$1.3388 \cdot 10^{-2}$	$4.73 \cdot 10^{-3}$	5.64	70
Fig. 10c	3.25	0.1931	$1.1684 \cdot 10^{-2}$	$5.57 \cdot 10^{-3}$	7.01	70
Fig. 10d	3.5	0.1798	$1.2108 \cdot 10^{-2}$	$5.47 \cdot 10^{-3}$	5.19	71

It can be observed that all the four distributions suitable for photon guiding, that the distributions of **Fig. 10b** is a preferable condition, and the distributions of **Fig. 10c** and **Fig. 10d** are more preferable conditions for photon guiding.

Table III reports the complete results of the simulation, wherein R is varied between 0.15 and 0.45.

In particular, Table III shows, for each possible combination of values of the parameters R, n, the value of the ω_n that allows maximizing the guiding effect.

TABLE III

R	n = 1.5	n = 2	n = 2.5	n = 3.25	n = 3.5
0.15	0.3862	0.2908	0.233	0.1796	0.1669
0.18	0.3879	0.2925	0.2348	0.1813	0.1685
0.21	0.3905	0.2955	0.238	0.184	0.1711
0.24	0.3943	0.2999	0.2421	0.1879	0.1748
0.27	0.3996	0.306	0.248	0.1932	0.1799
0.3	0.4066	0.3142	0.256	0.2005	0.187
0.33	0.416	0.3254	0.2671	0.2107	0.1968
0.36	0.4283	0.3405	0.2823	0.2246	0.2103
0.39	0.4441	0.3605	0.3028	0.2439	0.229
0.42	0.4638	0.3875	0.3321	0.2741	0.259
0.45	0.4902	0.4299	0.3859	0.3409	0.3295

In Table III, three areas have been delimited by different lines, to identify

preferred conditions of photon guiding, by taking into account not only the values of σ and N but also the other parameters that characterize the group velocity distribution. In particular, the thin line identify possible conditions of photon guiding, double thin line identify more preferred conditions of photon guiding and heavy line identify still more preferred conditions of photon guiding.

Table IV indicates, for each couple of values (R, n) the percentage of points of the group velocity distribution within an angular range of $\pi/9$ about the considered propagation direction, in relation with the optimum values of ω_n detected for each couple, i.e. in relation to the values of Table III. The analysis has been restricted to the ranges of values of more interest. Areas corresponding to the preferred conditions of photon guiding have been delimited by different kind of lines, as in Table III.

TABLE IV

R	n=2	n=2.5	n=3.25	n=3.5
0.21	38%	53%	62%	64%
0.24	51%	66%	73%	69%
0.27	64%	70%	70%	71%
0.3	64%	69%	72%	70%
0.33	68%	71%	70%	72%
0.36	68%	70%	72%	72%
0.39	65%	70%	72%	73%
0.42	65%	69%	74%	71%
0.45	50%	86%	72%	71%

Table V shows the value of variance σ^2 corresponding to the sets of values of Table III. The analysis has been restricted to the ranges of values of more interest. Areas corresponding to different conditions of photon guiding have been delimited by different kind of lines, as in Table III.

TABLE V

R	n = 2	n = 2.5	n = 3.25	n = 3.5
0.21	0.025	0.020	0.018	0.018
0.24	0.018	0.013	0.012	0.014
0.27	0.017	0.013	0.012	0.012
0.3	0.015	0.013	0.011	0.016
0.33	0.013	0.012	0.011	0.011
0.36	0.014	0.012	0.011	0.010
0.39	0.015	0.011	0.011	0.011
0.42	0.014	0.013	0.010	0.009
0.45	0.019	0.013	0.010	0.012

This example shows that it is possible to determine terns of values of *R*, *n* and ω_n that identify conditions of photon guiding.

Example 2

The same simulation has been performed for a photonic crystal having a square array of holes. Differently from above, the percentage of points originally in a range of $\pi/2$ about the considered propagation direction that have been concentrated within an angular range of $\pi/6$ is now considerd. The parameters R and n have been varied between 0.15 and 0.45 and between 2 and 3.5, respectively. Table VI reports the results of this simulation. In particular, Table VI shows, for each possible combination of values of the parameters *R*, *n*, the value of ω_n that allows maximizing the guiding effect.

TABLE VI

R	n = 2	n = 2.5	n = 3.25	n = 3.5
0.15		0.2043	0.1554	0.1444
0.18		0.2029	0.1563	0.1455
0.21		0.2045	0.1579	0.1469
0.24		0.2077	0.1602	0.1492
0.27		0.2104	0.1636	0.1522
0.3	0.2655	0.2154	0.168	0.1568
0.33	0.2724	0.2223	0.1745	0.163
0.36	0.2819	0.2323	0.1836	0.1719
0.39	0.2944	0.25	0.1955	0.183
0.42	0.3109	0.263	0.2149	0.2028
0.45	0.3374	0.2972	0.2582	0.2487

As above, areas corresponding to a possible condition and a more preferred condition for photon guiding have been delimited by a heavy line and a thin line, respectively.

Example 3

X-crossing without cross-talk in a photonic crystal according to the present invention has been demonstrated by a numeric simulation.

The simulation has been performed by considering a triangular array of holes filled with air, with a period *a* of 0.372 μm. The bulk refractive index *n* is 3.5, the normalized spacing *R* is 0.42 and the normalized frequency ω_n is 0.24. Two beams of light A, B at wavelengths 1550 nm, having a width of about 5 μm are propagated at 60° from each other along two crystal axes. Only the mode TM is considered. Propagation is simulated in a plane x-y, with input of light at y=0 μm. **Fig. 11** shows the propagation of the two beams A, B within the photonic crystal. It can be appreciated that the beams interfere with no cross-talk.

Example 4

A numeric simulation has been performed for demonstrating the flexibility of the

photon guiding technique of the present invention, in particular the possibility of guiding light beams of different dimensions in different positions of the crystal. The same conditions of Example 3 are considered. Three beams of light A, B, C of different width and at a wavelength of 1550 nm are propagated along a same direction of the crystal. **Fig. 12** shows the collimated propagation of the three beams A, B, C.

Example 5

A further numeric simulation has been performed for determining the behavior of a light beam at the interface between a photonic crystal according to the present invention and an integrated waveguide of a known type. **Fig. 13** shows, in a plane x-y, a photonic crystal 800 according to the present invention and a conventional integrated waveguide 801. The interface is represented by a line 802 at coordinate y=0.

The photonic crystal 800 has a triangular array of holes filled of air and a bulk refractive index *n* of 3.5. The normalized spacing *R* is 0.33 and the operative wavelength is 1550 nm. The normalized frequency ω_n is 0.188.

Waveguide 801 is a monomode waveguide, having a width of 4.5 μm, a core refractive index of 3.5 and a refractive index step of 0.01. This waveguide simulates, for example, a ridge waveguide. The bulk material is the same as that of the photonic crystal.

A normalized intensity of the input beam is detected at a detection point DP distant 5 μm from the interface 802. It has been observed that the beam intensity at DP is about 98.76% of the input beam intensity. It has also been observed that losses at the interface 802 are small.